The effect of uncertain floodplain roughness in hydrodynamic flood simulations

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In the Netherlands, 2D-hydrodynamic simulations are used to evaluate the effect of potential safety measures against river floods. In the investigated scenario's, the floodplains are completely inundated, thus requiring realistic representations of hydraulic roughness of floodplain vegetation. The current study aims at providing better insight into the uncertainty of flood water levels due to uncertain roughness characteristics in the floodplains. The study focusses on three key elements in the uncertainty of floodplain roughness: (i) the uncertainty of ecotope classifications in the floodplains, (ii), the uncertainty that arises from translating ecotopes to floodplain roughness and (iii) the effect of spatial differentiation of ecotope units.

To assess the effect of the first error source, new realisations of ecotope maps were made based on the current ecotope map of the Netherlands and an error matrix of the classification. For the second error source, field measurements of vegetation structure were used to obtain uncertainty ranges for a representative floodplain roughness cover. To investigate the effect of spatial differentiation, the size of ecotope units in the hydrodynamic model has been varied. It is shown that the various error-sources lead to uncertainty ranges of predicted water levels of the order of decimeters.

The quantification of the uncertainty in water levels will help to make better decisions on suitable flood protection measures. Moreover, the relation between uncertain floodplain roughness and the error bands in water levels may serve as a guideline for the desired accuracy of floodplain characteristics in hydrodynamic models.

Keywords—rivers, Rhine, hydraulic roughness, vegetation, hydrodynamic modelling, floodplains, ecotope maps, error propagation

1. Introduction

Accurate water level prediction for the design discharge of large rivers is of main importance for the flood safety of large embanked areas, as they are relevant for the height of the embankments, and to inform the communities on possible evacuation and for risk assessment. However, at this moment there is no quantification of the required accuracy of the model output. The order of magnitude of the error in water level is reported in several studies. In a study by Huthoff and Stijnen (2005) a 1-dimensional flow model was used to investigate the efficiency of an emergency retention area under uncertain flood levels. Several uncertainty sources, including floodplain roughness, led to water level uncertainties of several decimeters. Also, Stolker et al. (1999) modeled differences in water level using a 1D model and showed that in case 10 % of the land cover in the floodplain is changed from meadow to reed over a 10 km stretch of river, the peak increase in water level is 15 cm. Huthoff and Augustijn, (2004) report an 8 cm change in water level and stress the effect of the shape of the cross section of the river. In contrast to the mentioned works, no studies have been carried out using a two-dimensional model, nor has any information on the actual quality of the data been used that lies at the base of the roughness maps.

Currently, the vegetation map of the lower Rhine and Meuse floodplains is based on ecotopes. Mapping of ecotopes within the lower Rhine floodplain is based on visual interpretation and manual classification of vegetation units from aerial photographs (Jansen and Backx, 1998). Uncertainty in classification of the terrestrial ecotopes of the Rhine branches has been determined by Knotters et al. (2008) as "map purities", referring to the percentage of the mapped area that is correctly classified. Recently, a validation of the ecotope map has been carried out (Knotters et al., 2008). The map purity for the ecotope map of the Rhine branches of 2005 is estimated at 37% for 41 in the field distinguished different ecotopes (based on 406 field observations). The overall accuracy of this map is 69%

when aggregated to eight terrestrial ecotope groups (Knotters and Brus, Subm.). Other studies reported accuracies between 74 and 92% (Townsend and Walsh, 2001; Van der Sande et al., 2003; Geerling et al., 2007; Straatsma and Baptist, 2008). The effects of this classification error on water level and the distribution of water over the distributaries has not been investigated before. Also, the effects on the hydrodynamics of the within class variation is not known. Ecotopes are not homogeneous with respect to vegetation structure (vegetation height and density). The within-class variation of vegetation height and density may be as much as a factor 10.

Within a multitude of uncertainty sources, we focus on the effects of hydrodynamic roughness of vegetated floodplains on hydrodynamics. In particular, our aim is to quantify the effects of three error sources: (1) classification errors in the ecotope map, (2) uncertainty of vegetation structural parameters within one ecotope class (“within class variation), and (3) the effect of spatial differentiation in uncertain vegetation characteristics.

2. Study area

Within this study, we looked at the distributaries of the river Rhine in the Netherlands, which has an average water gradient of 0.10 m/km.. At the Dutch-German border, the river Rhine has an average discharge of 2250 m3/s, draining a catchment area of 165,000 km2. Entering from Germany, the river Rhine bifurcates into the "Pannerdensch Kanaal" and the Waal river at the "Pannerdensche Kop" (PK) bifurcation point, where roughly one third enters the "Pannerdensch Kanaal" and two thirds are conveyed into the river Waal. Another bifurcation occurs at the "IJsselkop" (IJK), where roughly one third of the discharge enters the right hand channel named the IJssel river and two thirds flow into the Nederrijn river (Fig. 1). The total embanked area amounts to 440 km2, the floodplain area is 320 km2 out of which 48 km2 consists of lakes and side channels. The vegetated area takes up 62 % of the total embanked area. Groynes fixate the main channel and limit the width of the main channel to 250, 160, 105 m for the Waal, Nederrijn and IJssel river, respectively. The cross-sectional width between the primary embankments varies between 0.5 and 2.6 km. Meadows dominate the land cover, but recent nature rehabilitation programs led to increased areas with herbaceous vegetation, shrubs and forest.

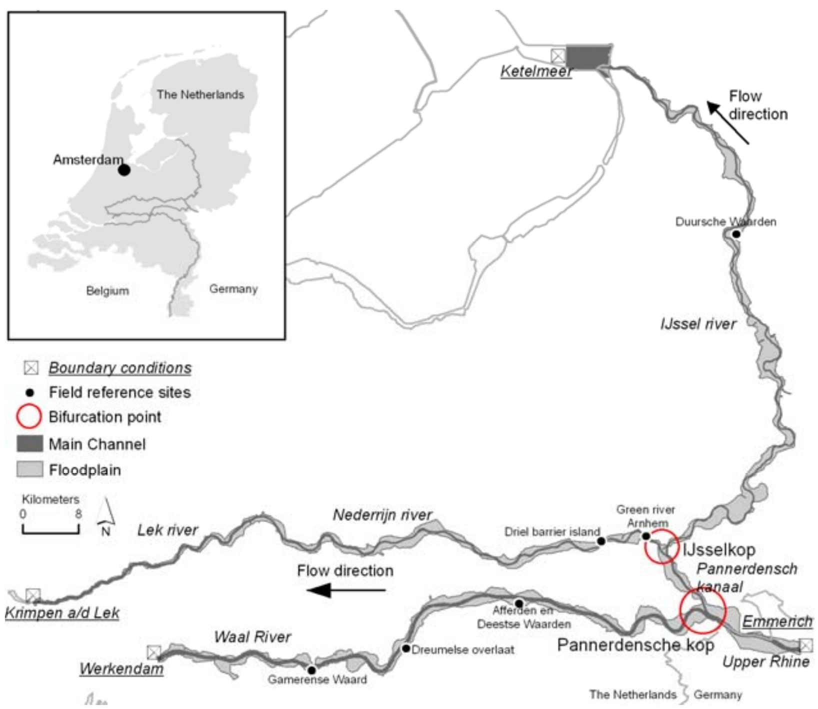

Figure 1. Study area showing the main distributaries of the river Rhine; Waal, Nederrijn/Lek and IJssel river.

3. Methods

3.1 Waqua

For this study we used the two-dimensional hydrodynamic model WAQUA (RWS, 2007). The model that was used for this study is based on a staggered curvilinear grid. Each of the 886,861 cells represents a column shaped volume of water with a variable surface area of 1000 m2 on average. The water flow between the water volumes in the raster is calculated by numerically solving the Saint-Venant equations of mass balance and of convective and diffusive motion in two dimensions (RWS, 2007) using a finite difference method. The boundary conditions of the model are the river discharge at the upstream boundary, and the water level at the downstream boundary using a discharge-stage relationship. Input data from which the WAQUA model calculates the water flow are a Digital Terrain Model (DTM), barriers and a roughness map. We ran the hydrodynamic calculations with a steady discharge of 16,000 m3/s at the upstream boundary, located at Emmerich, Germany. Water levels at the downstream model boundaries were around 4.39, 2.02 and 0.42 m above ordnance datum for the Waal, Nederrijn-Lek and IJssel rivers respectively. Roughness of the floodplain surface is derived from the Netherlands ecotope map. Ecotopes are aggregated into vegetation types according to the vegetation handbook of Van Velzen et al. (2003). The vegetation types are linked to vegetation structural parameters, such as vegetation height and density plus bottom roughness and drag. Subsequently, the structural parameters are used as input in the vegetation roughness equation proposed by Klopstra et al. (1997), which is implemented in WAQUA.

3.2 Classification errors

Map purities describe the proportion of the map that is correctly classified and the proportions that are made up of different classes. Ecotope polygons in the WAQUA Rhine model can sometimes cover several square kms, thus resulting in roughness modification on an equally large spatial scale. In reality, it is unlikely that such large areas are classified entirely wrong. With a larger size of the ecotope, more information is available to the interpreter and we can assume that less errors are made in classifying larger polygons. Therefore, to standardize the size of the polygons where the classification error is applied to, we also generated new roughness maps where ecotope polygons were made equal to the WAQUA computational grid. These gridcells have a typical size of 20 by 20 m.

3.3 Within class variation of vegetation structural characteristics per vegetation type

To fill the knowledge gap on the hydrodynamic effects of within class variation, we analyzed a database of vegetation structural parameters that was compiled by Straatsma (2009) based on fieldwork in Dutch floodplains in winter between 2000 and 2007 (see ‘field reference sites’ in Figure 1). Based on these data, four combinations of structural parameters were chosen for each original vegetation type, to represent the natural variation observed in the field.

For submerged vegetation, the relevant structural parameters are vegetation height and density. For a number of classes, enough field data were present in the database and in that case the following procedure was followed. Data were divided in four classes, each containing an equal number of field reference measurements. The data were first divided by the median value of the vegetation density, and subsequently each of these two classes were subdivided by the median value of vegetation height (Figure 2). The mean and standard deviation were computed for the resulting four variations. In the majority of the cases, however, not enough field data was available, and the vegetation handbook by Van Velzen et al. (2003) was used as the starting point. The values for vegetation height and density that were chosen for these cases were based on expert judgment and the known distribution of vegetation parameters from similar vegetation types that did have enough field data. In general, multiplying the height and density by 0.5 and 2.0 made up the four classes.

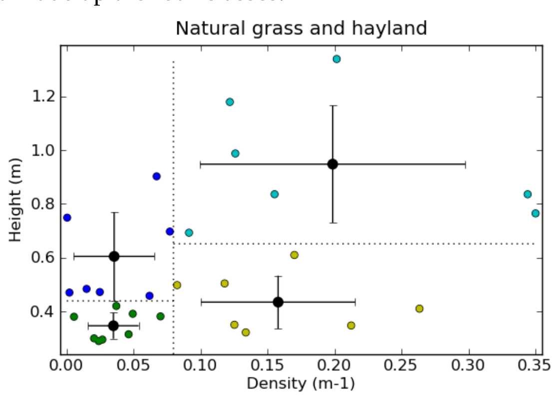

Figure 2. Variation of vegetation height and density for one of the submerged vegetation types. The large-sized dots represent the 4 structural parameter combinations that are used in the computations to study the effect of within class variation.

4. Results

We ran three sets of each 15 model runs to investigate the hydrodynamic impact of three error sources:

- ecotope classification errors at ecotope polygon level,

- ecotope classification error at computational cell level, and
- within class variation (of vegetation structural parameters) at computational cell level

Results were compared based on the predicted water levels on the river axis of the three main distributaries of the river Rhine and the discharge distribution over the bifurcation points. A steady state discharge of 16 000 m^3/s was chosen which is the same as the design discharge of the Rhine for the year 2015.

4.1 Effect on roughness

In Figure 3 an example is given of one of the realizations of roughness maps that are based on the ecotope map-purities (with roughness variation at the ecotope-polygon level). It can be seen that a relative large range of floodplain roughnesses are present in the study area, ranging from effective roughness heights of k_N = 0.01 to k_N = 10 m. Figure 4 shows the range in effective roughness heights between the different roughness-realizations. For this purpose, the standard deviation in k_N-values between the 15 realizations is used. It can be seen that for some ecotope types the standard deviation in effective roughness height as high a 1 m or more.

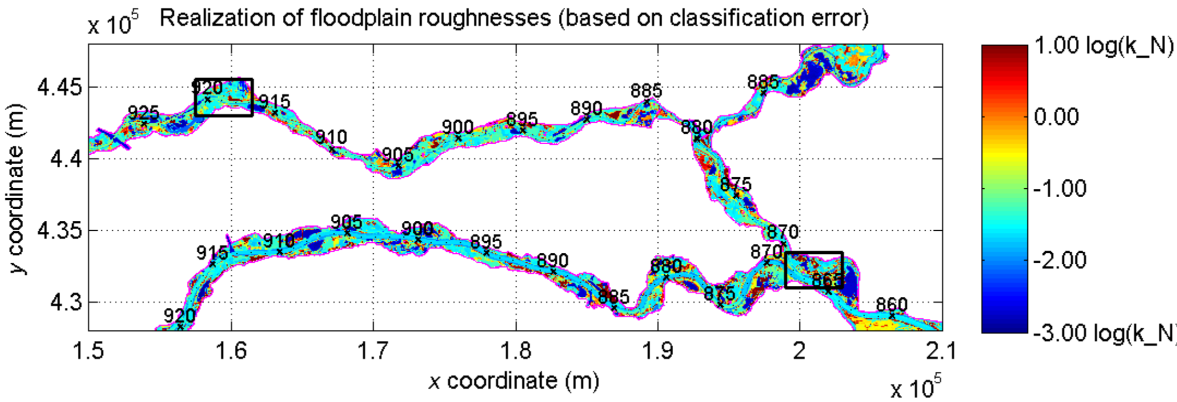

Figure 3. One of the 15 realizations with new floodplains roughnesses, based on the ecotope map purities (roughness variation at ecotope polygon level)

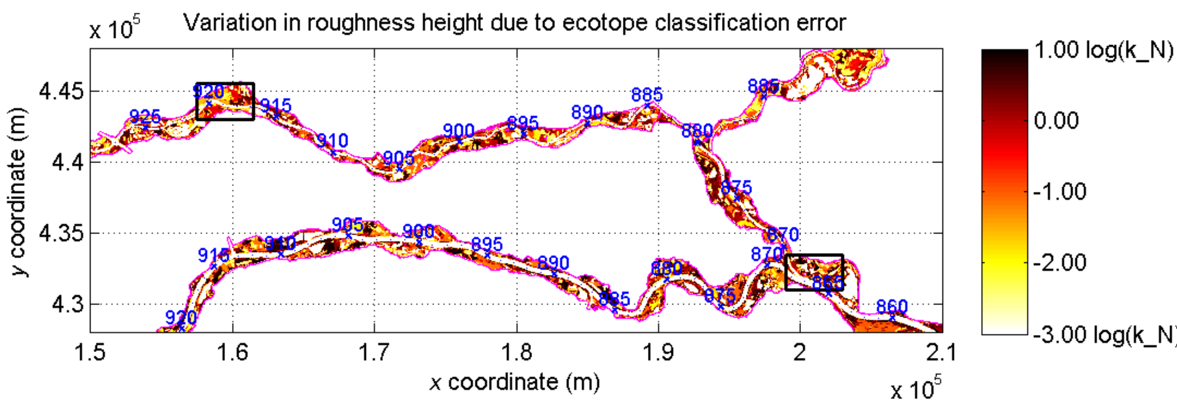

Figure 4. Local standard deviations in effective roughness heights (k_N-values), based on the 15 realizations of roughness maps (roughness variation at ecotope polygon level, based on map purities).

4.2 Effect on flow velocities and discharge distribution

Corresponding to the roughness characteristics shown in Figures 3 and 4, maps are made that show the localized effect on flow velocities and on water levels. In Figure 5 the standard deviation of the resulting flow velocities is shown. A comparison with the roughness variations in Figure 4 reveals that, in general, flow variations are largest where roughness variations are largest. However, as some parts of the floodplain contribute only little to the conveyance of the river, in these parts large roughness variations have only little effect on flow velocities. The strongest variations in flow velocities are typically found at locations where water flows away from or into the main river channel.

The average effect on the discharge distribution is a variability of 170, 163, 155, and 163 m^3/s for the Waal, Pannerdensch Kanaal, Nederrijn and IJssel river, respectively (Table 1). These values are based on classification errors at polygon level. The effects of the classification errors at cell level and the within class variation is much smaller. The within class variation shows the smallest effect.

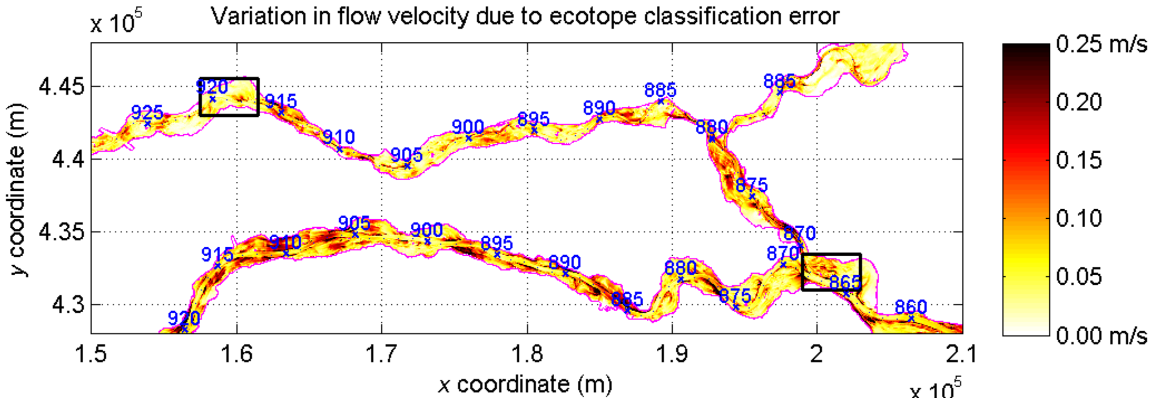

Figure 5. **Local standard deviations in flow velocities, based on the 15 realizations of roughness maps (roughness variation at ecotope polygon level, based on map purities).**

Table 1. Variation in discharge distribution of different stochastic errors (m^3/s)

	Waal	Pannerdensch Kanaal	Nederrijn	IJssel
Standard deviation				
Classification error at polygon level	47	46	43	56
Classification error at cell level	12	8	10	7
Within class variation	7	5	4	5
Range				
Classification error at polygon level	170	163	155	163
Classification error at cell level	58	38	31	23
Within class variation	29	16	13	21

4.3 Effect on water levels

In Figure 6 the local variations in water levels are shown. These result, again, correspond to the roughness variations due to ecotope classification error at the polygon level. In the figure it can be seen that the standard deviation of water levels can be as large as 10 cm at several locations. A comparison between the results in Figure 5 and 6 shows that large variations in flow velocities not necessarily lead to large water level differences.

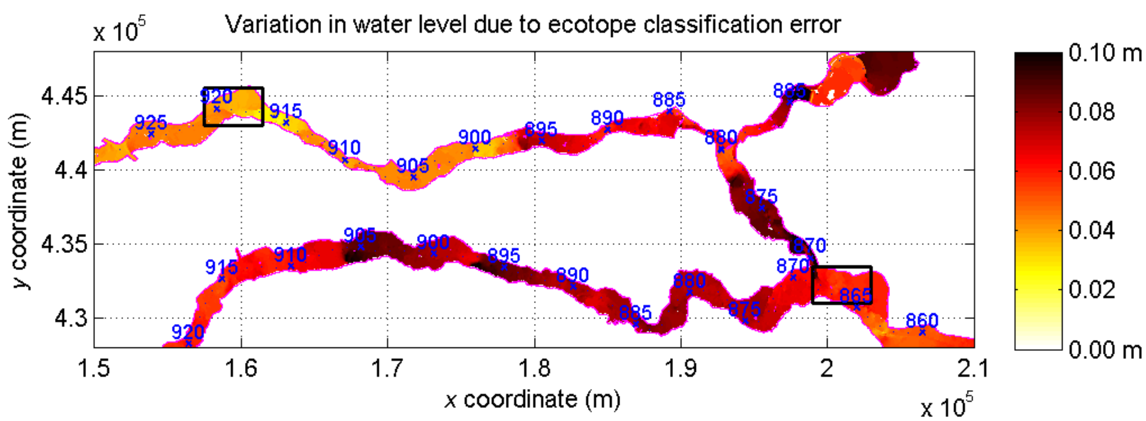

Figure 6. **Local standard deviations in water levels, based on the 15 realizations of roughness maps (roughness variation at ecotope polygon level, based on map purities).**

Figure 7 shows the variations in water levels along the axis of the river for the three investigated error sources: (a) classification errors at ecotope polygon level, (b) classification error at computational cell level, and (c) vegetation structure (within class variation). The outcome of the individual model runs is shown as thin grey lines. The spatial overview of the range in water levels in Figure 6 corresponds to the results in Figure 7a. In Figure 7 the results are presented as variations around the mean predicted water level of the 15 model runs. Data has been summarized for the following river sections: (1) Bovenrijn-Waal, (2) Pannerdensch Kanaal-Nederrijn-Lek, and (3) IJssel. The variation is summarized by the range and difference between the 84 and 16 percentile in water levels for each river kilometer at the river axes. The maximum range in water levels is 0.40, 0.40 and 0.57 m for the different river sections. The larger range for the IJssel river results from the large fractional discharge at this distributary. Note that the variation at the model boundaries is limited due to the applied discharge-water level relationship. The variation of the water level at the boundaries resulted purely from the variation in discharge.

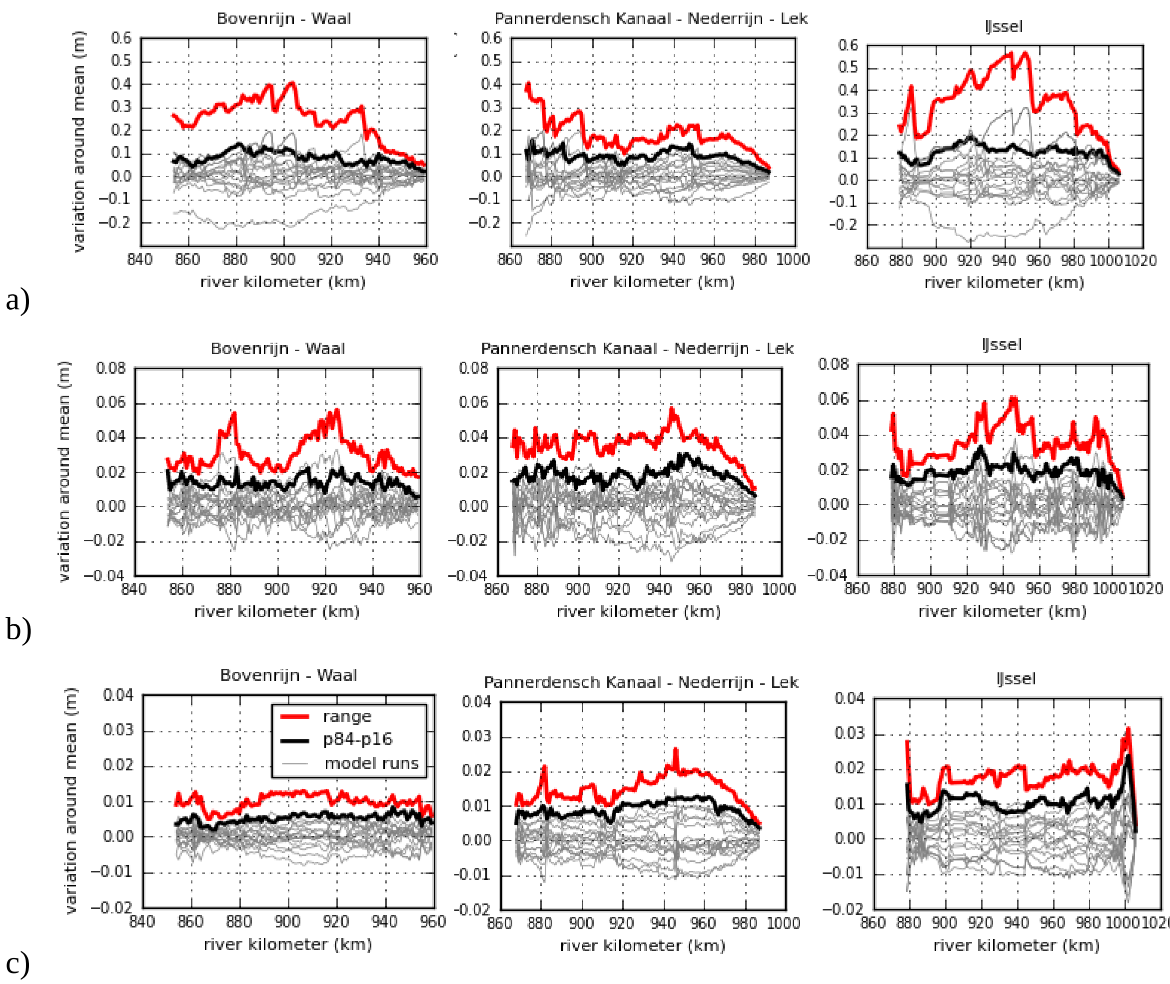

Figure 7. **Variations in water levels for different error sources: (a) classification errors at ecotope polygon level, (b) classification error at computational cell level, and (c) within class variation. Note the different vertical axis between the a, b, and c.**

5. Discussion

In the previous section, we looked at the hydrodynamic effects due to different error sources related to vegetation roughness in floodplains. In general, the effects are relatively large when compared to the accuracy required for the hydraulic boundary conditions in the Netherlands. For landscaping measures the effect should be less than 2 mm rise in water level at the river axis and less than 5 m^3/s change in discharge distribution over the bifurcation points.

The 69% classification error leads to a large range in water levels if applied to the ecotopes, and a much smaller effect when applied at cell level. We conducted computations because the validation of the ecotope map is still a matter of debate. In the field, the support for the measurements was much smaller than in for the aerial image interpretation. Therefore some of the within class variation would show up as misclassifications in the error matrix of Knotters et al. (2008). Due to the mismatch in spatial support, we could not assess whether a relation exists between the classification accuracy and the size of the polygons. It seems logical that large polygons will be classified better, but this assumption can not be substantiated with data. Our results show the extreme end of this classification error. The large effect of the classification error on the water levels and discharge distribution points at the need for an undisputed quality assessment of the ecotope map.

Another implication of the error propagation of the classification error is that a relation could be established between the classification accuracy and the variation in water levels. In the present study we linked a 69 % classification accuracy to a maximum range in water levels is 0.40, 0.40 and 0.57 m for different considered rivers sections. For a higher classification accuracy the variation in water levels will be smaller as more of the polygons will maintain their class. Based on such a relation a political choice can be made about the accepted amount of uncertainty that the river manager is willing to allow for the water levels. This uncertainty in water levels can then be translated into a classification accuracy. A tangible benchmark for classification accuracy that is substantiated by research would be a stimulation for the remote sensing community to provide the optimal method to reach this goal.

The within class variation in four classes that was applied randomly to the roughness files resulted in a cm variation in water levels. This is a rather small effect compared to classification errors. However, in assigning the vegetation structural characteristics only little field data was available for most classes. Preferably, a complete database would ground the choices for the lookup table and the within class variation.

Because of the computational demands of the WAQUA model of the Rhine branches, in the current study the number of individual runs was limited to 15. The question arises whether enough runs were done to reliably estimate the range in expected water levels. It appears that the variation in range stabilizes after around 6 model runs, but the fifteenth run was again an exceptional distribution of ecotopes leading to an even higher range for the Waal and IJssel river. The standard deviation of computed water levels converged to a stable value after about 10 model runs (results not shown here). Fifteen model runs are therefore suggested for future probabilistic studies.

The habitual parameter to calibrate a hydrodynamic model is the roughness of the main channel. This study shows the possible range in values that result from assuming that the floodplain roughness is not correct. In theory, it would be possible to calibrate a flow model on different ecotope distributions as well in a probabilistic manner. Given a discrepancy between model outcome and measured values of water level, or flow velocities, different ecotope distributions can be tested against the measured values. The obvious disadvantage is that no direction for searching can be defined beforehand, making the calibration process more time consuming.

The complex system of hydrodynamics that we try to capture in a model has many uncertainties (location, level, and nature). In this study, we quantified the effects of spatial variability of vegetation roughness. Within the ongoing project of uncertain reduction within Flood Control 2015 other aspects are captured, such as morphological changes at the bifurcation points, design discharge and operational discharge prediction. The uncertainties of these other sources should be compared in a final study. One such aspect is the operational work of predicting the water levels during a flood. For this work a 1D model is used, but the sensitivity of this model for roughness parameterization should be studied in more detail.

The quantification of the uncertainty in water levels and discharge distribution will help to make decisions more realistically as the error bands are substantiated. It can also influence the assessment of the height of the embankments as insight is given in the variability of the outcome of the flow models at design discharge. Moreover, the error bands may serve as an incentive to quantify the desired accuracy in the vegetation structural characteristics. This means that an upper limit can be put on the variation in water levels that is accepted from errors in the roughness

6. Conclusions and recommendations.

In this study, the variation in water levels has been studied resulting from two error sources: (1) classification error (at polygon and cell level), and (2) incorrect values in the lookup table relating ecotopes to vegetation height and density. We conclude that:

1. The classification error at polygon level leads to a difference in 84th and 16th percentile of the predicted water levels per river kilometer of 0.15, 0.15 and 0.20 m for Upper Rhine- Waal, Pannerdensch Kanaal-Nederrijn-Lek and the IJssel river respectively. The range is maximum range in water levels is 0.40, 0.40 and 0.57 m for these river sections respectively. Largest effects are found in the IJssel river and the Pannerdensch Kanaal. The effect of classification accuracy on polygon size is not taken into account in this study.
2. At cell level, the 84th minus 16th percentile range is 0.02, 0.03 and 0.035 m for the Upper Rhine- Waal, Pannerdensch Kanaal-Nederrijn-Lek and the IJssel river respectively. These values are much lower then what was found for variations at the polygon level, demonstrating the need to unambiguously link map

purities to a spatial scale.

3. The within class variation (at cell level) leads to variation in water levels of 0.01, 0.015, and 0.02 m for Upper Rhine- Waal, Pannerdensch Kanaal-Nederrijn-Lek and the IJssel river respectively.
4. The discharge distribution at the Pannerdensche Kop bifurcation point is maximum 170 m^3/s for classification error at polygon level. Effects of classification error at cell level and within class variation is five times smaller.
5. Priority should be given to increasing the classification accuracy as this generates the largest error.
6. The suitable number of runs for a probabilistic assessment of classification accuracy might be fifteen.

With this study, we explored the relationship between vegetation parameterization and the effects on predicted water levels. The next step would be to establish the relationship between classification accuracy and the range in water levels to stimulate the remote sensing community to provide user-oriented information and the water management to choose a required accuracy level for the prediction of peak water levels.

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